

Indoor clothing insulation and thermal history: A clothing model based on logistic function and running mean outdoor temperature

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ABSTRACT

Predicting the pattern of clothing adjustment to climate change can provide important basis for thermal comfort and energy consumption analysis. This study proposed a clothing model (IC-RM model) to predict indoor clothing insulation based on people's thermal history. In the IC-RM model, the running mean (RM) outdoor temperature (exponentially weighted running mean of the past outdoor temperatures) was used as the outdoor climate index to reflect the thermal history. Different from the existing models, the IC-RM model adopted a four parameters logistic function to fit the relation between indoor clothing insulation and the RM outdoor temperature. A longitudinal thermal comfort survey (13 months) was conducted in two different types of naturally ventilated building in Changsha China. The decreased freedom of clothing adjustment at high/low outdoor temperatures and notable effects of the past outdoor temperatures on the indoor clothing insulation were observed. The IC-RM model was implemented using 1427 useful clothing records collected during the survey. The high R^2 value (> 0.9) for the IC-RM model indicated that the proposed model provides an effective method to quantify the change of indoor clothing insulation based on the effect of thermal history. Compared with linear, exponential and power functions, the logistic function exhibited better performance in quantifying the tendency for the variation in the indoor clothing insulation with the RM outdoor temperature.

1. Introduction

Clothing can be described in physical term of thermal insulation for the heat exchange of man with his immediate thermal environment [1]. In thermal comfort theory, clothing insulation is an important factor that affects thermal sensation [2]. People can adjust their clothing insulation to suit their own thermal comfort requirement [3,4] and reduce energy consumption in buildings [5]. Therefore, clothing adjustment is a powerful behavioural adaption mode to weather change [6,7]. Predicting the pattern of clothing adjustment to weather change provides important basis for thermal comfort and energy consumption analysis [8,9].

Outdoor temperature is an important climatic factor to the change of indoor clothing. Various models were developed to predict the change of indoor clothing insulation with outdoor temperature, based on different regression functions. de Dear and Brager used an exponential decay function to fit the change of the mean clothing insulation for occupants of each building with the mean outdoor effective temperature at the time of the survey, based on ASHRAE RP-884 database. According to this model, 40% of the variance in clothing

insulation was explained by variations in the outdoor climatic index [10]. Nicol et al. developed regression models for the change of mean clothing insulation with daily mean outdoor temperature on the day of the survey, based on the field surveys conducted in five cities of Pakistan [11]. Their results show that the cubic function and the linear function explained 90% and 80% of the variance in clothing insulation, respectively. Morgan and de Dear examined the day-to-day variation in indoor clothing insulation in a shopping mall and a call centre in Sydney, Australia [8]. A power function and an exponential function are developed to reflect the decrease in average clothing insulation with increased mean daily outdoor temperature in the shopping mall and the call centre, respectively. Both model explained about 45–55% of the variance of clothing insulation. Carli et al. used linear regression functions to quantify the relationship between the daily maximum, minimum and mean clothing insulation and four types of outdoor temperatures including outdoor temperature at 6 a.m., mean daily outdoor temperature, mean monthly outdoor temperature and weighted outdoor temperature over the last 4 days, respectively [12]. They found that the outdoor temperature at 6 a.m. gave the highest explanation (31%) for the variation in clothing insulation in naturally

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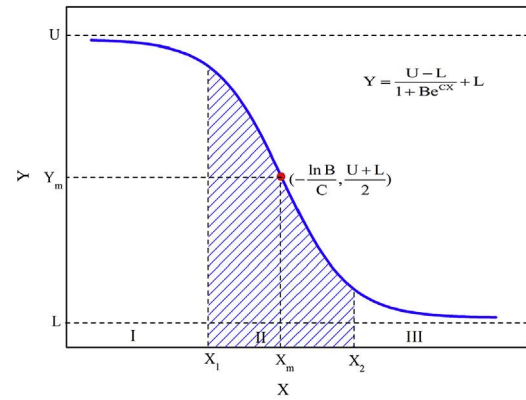
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ventilation buildings. Their data was from the RP-884 database and field measurements in Singapore and Indonesia. Haldi and Robinson performed linear regression between clothing insulation and daily mean outdoor temperature throughout the preceding 24 h, using the data from a field survey conducted in Switzerland [13]. The model explained 40% of the variation in clothing insulation due to the change of outdoor temperature. Schiavon and Lee proposed a dynamic clothing model for thermal comfort standard based on 6333 selected observations from ASHRAE RP-884 database [14]. They applied linear and exponential functions to fit the relationship between clothing insulation and outdoor air temperature at 6 a.m., which predicted 19% of the total variance in clothing insulation. Carvalho et al. used linear function to relate clothing insulation with the daily maximum outdoor temperature and mean temperature of previous days, based on a field survey conducted in two naturally ventilated buildings in Leiria, Portugal [15]. Their results showed that the mean outdoor temperature on previous day had a higher weight (81%) than daily maximum temperature (19%) on the clothing insulation.

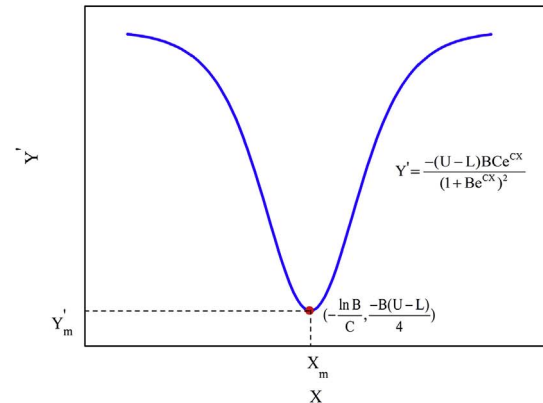
These above models have two limitations for the prediction on clothing insulation. On the one hand, the linear function, as used by most of the existing models, is not able to reflect the diminished degree of freedom for clothing adjustment with the outdoor temperature becoming high in summer and low in winter. The diminished degree of freedom means that people are less likely to vary the amount of clothing they wear. Though the exponential and power functions described the reduced variation in clothing insulation under high outdoor temperatures, they failed to reflect the similar trend under low outdoor temperatures. These shortcomings restrict the reliability of these models in the prediction of indoor clothing insulation, especially under hot and cold climate conditions. As shown in Fig. 1(a), the curve for the logistic function is accordant to the trend of the clothing insulation with climate change. Therefore, the logistic function is expected to fit the pattern of clothing change better.

On the other hand, these models used current outdoor temperatures as the outdoor climatic index to predict the indoor clothing insulation. However, the fact is that the real time climate information cannot be known in advance. If forecast outdoor temperatures are used, this will cause deviation. Some studies revealed the important effect of the thermal history on the clothing adjustment [e.g. 8, 15]. That is to say, the past outdoor temperatures significantly influence the indoor clothing insulation. Based on such effect, the information on past outdoor temperatures should be able to provide basis to predict indoor clothing insulation. The running mean (RM) of the outdoor temperature (exponentially weighted running mean of the past outdoor temperatures) can well reflect the thermal history, which has been successfully applied in the adaption thermal comfort models for the European standard (EN 15251) [16]. Since clothing insulation is an important factor to thermal comfort, it is expected that the RM outdoor temperature is also suitable for the prediction of indoor clothing insulation. Only a few studies used the RM outdoor temperature as a predictor for indoor clothing [17,18]. However, the details of the calculation for the RM outdoor temperature was not given in these studies. The method to determine the optimal RM outdoor temperature for the clothing change still needs to be investigated.

This study proposed a model to predict the change of indoor clothing insulation based on people's thermal history (past outdoor temperatures). The proposed model used the RM outdoor temperature as the predictor for indoor clothing insulation. Different from the existing models, a four parameters logistic function was adopted to fit the relation between the clothing insulation and the RM outdoor temperature. The proposed model can refine on the shortcomings of the existing models by using the logistic function and well reflect the cumulative effect of the past outdoor temperatures by using the RM outdoor temperature.



(a) The curve for four parameters logistic function



(b) The curve for slope of logistic function

Fig. 1. A four parameters logistic function for indoor clothing model. Y means clothing insulation, Y' variation rate of clothing insulation and X the RM outdoor temperature.

2. Method

2.1. The logistic function for indoor clothing model

People remove or add their clothing with increase or decrease in outdoor temperature to keep thermal comfort. However, there are two limits for the clothing insulation adjustment. On the one hand, clothing removal slows down until clothing insulation reaches the limit of a socially acceptable level at high outdoor temperatures, because wearing too less clothing cannot be accepted by the public, which is called “adaptive saturation” [19]. On the other hand, clothing addition slows down when clothing insulation increases towards the limit of a psychologically acceptable level at low outdoor temperatures, because adding too much clothing can make people feel uncomfortable and inconvenient. The decrease in freedom of clothing adjustment at high and low outdoor temperatures was observed by the existing studies [8,11,13,20] and the present work (see Section “Results”).

A four parameters logistic function is suitable to describe the variation in clothing insulation with outdoor temperature, given as follows [21,22].

$$Y = \frac{U-L}{1+Be^{CX}} + L \quad (1)$$

where Y is clothing insulation. U and L mean upper and lower limits for clothing adjustment, respectively. X means outdoor temperature. B and C are the regression coefficients of the model.

As reflected by the logistic function, the clothing adjustment behaviour can be divided into three sections, which depends on the

outdoor temperature (Fig. 1(a)). The middle section (2) is defined as rapid adjustment period. In this section, people can freely adjust their clothing according to the change of outdoor climate, as indicated by the rapid variation in clothing insulation. Sections 1 and 3, located on each side of section 2, are defined as slow adjustment period. In these two sections, the degree of freedom for clothing adjustment is very limited, as indicated by the slow variation in clothing insulation.

In equation (1), the upper limit U and the lower limit L reflect the psychologically acceptable maximum level and the socially acceptable minimum level of clothing insulation, respectively. The regression coefficients B and C determine the value of midpoint (X_m in Fig. 1(a)) for the logistic curve, which is calculated as,

$$X_m = -\frac{\ln B}{C} \quad (2)$$

And C indicates the steepness of the logistic curve.

The slope of the logistic curve reflects the variation rate of clothing insulation with outdoor temperature, which can be calculated as the derivative of equation (1),

$$Y' = \frac{-(U-L)BCe^{CX}}{(1+Be^{CX})^2} \quad (3)$$

The relation between the variation rate (negative value) of clothing insulation and outdoor temperature is described by a symmetrical curve similar to “U” type (Fig. 1(b)). The bottom of the curve indicates the maximum of the variation rate of clothing insulation.

The values of above four parameters in the logistic function can be obtained based on data from field investigation.

2.2. Calculation of RM outdoor temperature

The variation in indoor clothing insulation level is closely related to past outdoor temperatures with more recent experiences of outdoor temperature being more influential in the clothing insulation [8,13,15]. Therefore, the exponentially - weighted RM outdoor temperature was used as the outdoor temperature index in the logistic model to reflect the time-dependence influence of outdoor temperature experienced on clothing insulation. The RM outdoor temperature has been successfully applied in the adaptive thermal comfort model for European standard EN15251 [16] and Chinese people [23].

The RM outdoor temperature is defined as [16].

$$T_{rm} = (1 - \alpha)\{T_{t-1} + \alpha T_{t-2} + \alpha^2 T_{t-3} + \dots + \alpha^{n-1} T_{t-n}\} \quad (4)$$

where T_{rm} is the RM outdoor temperature at time t , the interval mean outdoor temperature (the mean for equal time interval - hours, days, etc.) at n time-intervals previously. α is time constant ($0 \leq \alpha < 1$) that quantitatively reflects the rate at which the effect of any past temperature decays.

The RM outdoor temperature at the i th time-interval ($T_{rm(i)}$) can be conveniently calculated based on the value of the running mean and the value of the mean outdoor temperature for the previous time-interval [16].

$$T_{rm(i)} = (1 - \alpha)T_{i-1} + \alpha T_{rm(i-1)} \quad (5)$$

where T_{i-1} and $T_{rm(i-1)}$ are mean outdoor temperature and RM outdoor temperature at time-interval $(i-1)$, respectively.

A bigger value of α indicates a greater effect of past outdoor temperatures.

2.3. A longitudinal survey in office buildings of Changsha China

Changsha China is the capital of Hunan province located in the south-central area of China (28°11'N, 112°58'E). A longitudinal survey was conducted in two different types of naturally ventilated building in

Changsha. The survey provided field data of indoor clothing insulation for the proposed clothing insulation model.

The two office buildings were located in the campus of Central South University. One building is a four-story building and houses offices for teachers and graduate students on two floors (the second and third floors). Another building is a courtyard house and hosts offices for only graduate students. Initially, both buildings were designed for naturally ventilation. Later, unit air-conditioners were equipped in most office rooms.

Two offices were selected for the survey. One office is a west-facing room on the third floor of the four-story building, which has an area of 40 m² (7.7 × 5.2 m) and a height of 3 m. Another office is a south-facing room in the courtyard building with an area of 43.2 m² (7.2 × 6 m) and a height of 4.5 m. There are operable windows, doors and a floor-standing air conditioner with cooling and heating mode in each office. Each office can accommodate 4–8 occupants.

15 graduated students (9 males and 6 females) working in the two offices were recruited. All subjects are healthy with mean±SEM of age: 23.9±0.6 years, height: 168.6±2.1 cm and weight: 59.9±2.6 kg. Each subject has lived in the university for more than one year. They conducted office related work, such as reading, writing and typing at a computer. Verbal and written informed consent were obtained from each subject prior to their participation in the survey. They can open windows and doors. They were allowed to use the air-conditioners and set the temperature freely. However, they were always asked to keep energy-saving in their mind. There was no restriction on their clothing at any time.

The survey was conducted daily from Jan. 2010 to Feb. 2011. In some holidays such as some days during summer and winter vacations (Jul. –Aug. 2010 and Jan. –Feb. 2011) and some weekends, the survey was not carried out. Every day the survey was done at three times (morning/afternoon/night) at most. The periods for the survey in morning, afternoon and night were respectively 10:30–11:30, 16:00–17:00 and 20:00–21:00. The graduated students are asked to work in their office before 22:00. The offices were closed at 22:00. All protocols were approved by the university's ethics committee and conformed to the guidelines contained within the Declaration of Helsinki.

During the survey, each subject, who was working in the office, was asked to fill out the electronic questionnaire reflecting their thermal comfort, clothing level and activity level. In the questionnaire the clothing garment checklist was written in Chinese without insulation values. The subjects selected their actual clothing from the garment checklist. At the same time the researcher carefully recorded the subjects' controls on window, door, curtain, fan and air-conditioner. Four indoor thermal environment parameters (indoor air temperature, humidity, velocity and global temperature) close to each subject at 1.1 m height were continuously monitored for 5 min. The time of each investigation spent in each office was about 30 min. The survey was done on the subjects being in the offices for longer than 20 min to eliminate the effect of a short residency time. The subjects were not required to stay at the offices all day for the survey. They were free to arrange their work in the offices. If they were staying in the offices during the survey time, they filled out the electronic questionnaire.

The longitudinal design of this survey used the same subjects during the whole period to eliminate the influence of individual difference. More details on the survey can be found in our published work [7].

2.4. Calculation of clothing insulation

The subjects in the offices were free to adjust their clothing. Clothing garments were carefully recorded on the questionnaire by the subjects during the survey. The clothing insulation value is expressed in clo unit. 1.0 clo is equivalent to 0.155 (m²·K)/W [22]. Table 1 lists the

Table 1
The effective garment insulation values.

Garment description	Insulation (clo)	Reference	Garment description	Insulation (clo)	Reference
Tops			Trousers		
Briefs or Panties + Bra	0.04	[24]	Straight trousers (thick)	0.24	[24]
T-shirt	0.08	[24]	Fibre-pelt trousers	0.35	[25]
Sleeveless vest (thin)	0.13	[24]	Short skirt	0.08	[24]
Sleeveless vest (thick)	0.22	[24]	Skirt (thin)	0.14	[24]
Long underwear top	0.2	[24]	Skirt (thick)	0.23	[24]
Short-sleeved, sweat shirt	0.17	[24]	Short-sleeved dress	0.29	[24]
Long -sleeved, sweat shirt	0.34	[24]	Long-sleeved shirtdress (thin)	0.33	[24]
Short-sleeved, dress shirt	0.19	[24]	Long-sleeved shirtdress (thick)	0.47	[24]
Long-sleeved, dress shirt	0.25	[24]	Socks		
Long-sleeved sweater (thin)	0.25	[24]	Ankle socks (thin)	0.02	[24]
Long-sleeved sweater (thick)	0.36	[24]	Ankle socks (thick)	0.05	[25]
Jacket (thin)	0.36	[24]	Long socks (thin)	0.02	[24]
Jacket (thick)	0.44	[24]	Long socks (thick)	0.1	[25]
Down jacket	0.55	[25]	Footwear		
Trousers			Sandals	0.02	[25]
Short shorts	0.06	[24]	Sport shoes	0.04	[25]
Walking shorts	0.08	[24]	Fibre-pelt shoes	0.09	[25]
Long underwear bottoms	0.15	[24]	Boots	0.1	[25]
Straight trousers (thin)	0.15	[24]			

effective garment insulation values used in this study [24,25].

The intrinsic clothing insulation of the composite ensemble was estimated based on following formula [24,26],

$$I_{cl} = \sum_i I_{clu,i} \quad (6)$$

where $I_{clu,i}$ is the effective insulation of garment I and I_{cl} is the insulation for the entire ensemble.

For the method of clothing insulation estimation, the main source of inaccuracy is in determining the appropriate values for individual garments in real conditions. Overall accuracies are on the order of $\pm 25\%$ for the application of the present method [24].

2.5. Meteorological data

Meteorological data during the period of the longitudinal survey were obtained from a local weather station, which is about 5 km away from the university. The data contains outdoor air temperature, humidity and wind speed recorded on an hourly basis. The data of the outdoor air temperature was used to calculate the RM outdoor temperature in this study.

2.6. Statistical analysis

The Multi-way ANOVA model was used to examine the significance of the difference in indoor clothing insulation between three time periods (morning, afternoon and evening) during the same day and between different days. The three time periods and days were included in the model as fixed factors. The subjects were also included as a fixed factor in the ANOVA model, considering that the samples of clothing at different time periods were collected from the same subject. Main effects were tested.

Pearson correlation analysis was used to evaluate the relevance between the clothing insulation and climatic parameters.

Linear, exponential and power models were used to fit the relationship between clothing insulation and the RM outdoor temperatures based on the field data from the long-term survey, respectively. The determination coefficient R^2 was used to indicate the goodness of fit.

The statistical analysis was performed with SPSS 19.0 software (SPSS Inc., Chicago, USA). The significance level was set at $p = 0.05$.

3. Results

3.1. The outdoor climate conditions

Changsha has a typical climate of hot summer and cold winter. The climate condition in each month over whole period of the longitudinal survey is shown in Fig. 2. The variation in the outdoor air temperature is large. As shown in Fig. 2, the monthly mean of outdoor air temperature reached the maximum of 30.8 °C in Jul. 2010 and gradually decreased to the minimum of 2.3 °C in Jan. 2011. However, the difference in the outdoor air velocity and humidity between different months was much smaller. The monthly mean air humidity ranged from 60% to 80% and the monthly mean air velocity varied between 0.5 and 1.6 m/s.

3.2. The indoor clothing insulation

The samples for air conditioning environment were not included. After a careful check, the abnormal samples were excluded. Finally, total 1427 clothing records collected on 222 days were used for the analysis. Table 2 lists the statistical results of clothing insulation in different seasons. During the whole survey period, the maximum of clothing insulation was 1.88 clo in winter, while the minimum was 0.2 clo in summer. The clothing ensemble for the maximum insulation included panties and bra, long underwear top, long underwear bottoms, long-sleeved sweaters (thick), wool blend pants (high-insulative), jacket (thick), trousers (thick) and boots. For the minimum insulation, the clothing ensemble consisted of panties, very cool suspender skirt (nearly a combination of bra and short thin skirt) and sandals for female.

The number of samples in morning, afternoon and evening were 441, 473 and 513 respectively. There was no significant difference in the clothing insulation between morning, afternoon and evening ($p = 0.772$). However, the difference in the clothing insulation between different days was significant ($p < 0.001$). Therefore, the analysis on the field data was performed on the basis of daily mean. The mean clothing insulation was calculated for each day. The daily mean outdoor temperature was calculated using the hourly data from the local weather station.

Fig. 3 shows the day to day change of daily mean clothing insulation and daily mean outdoor temperature. The clothing insulation had an

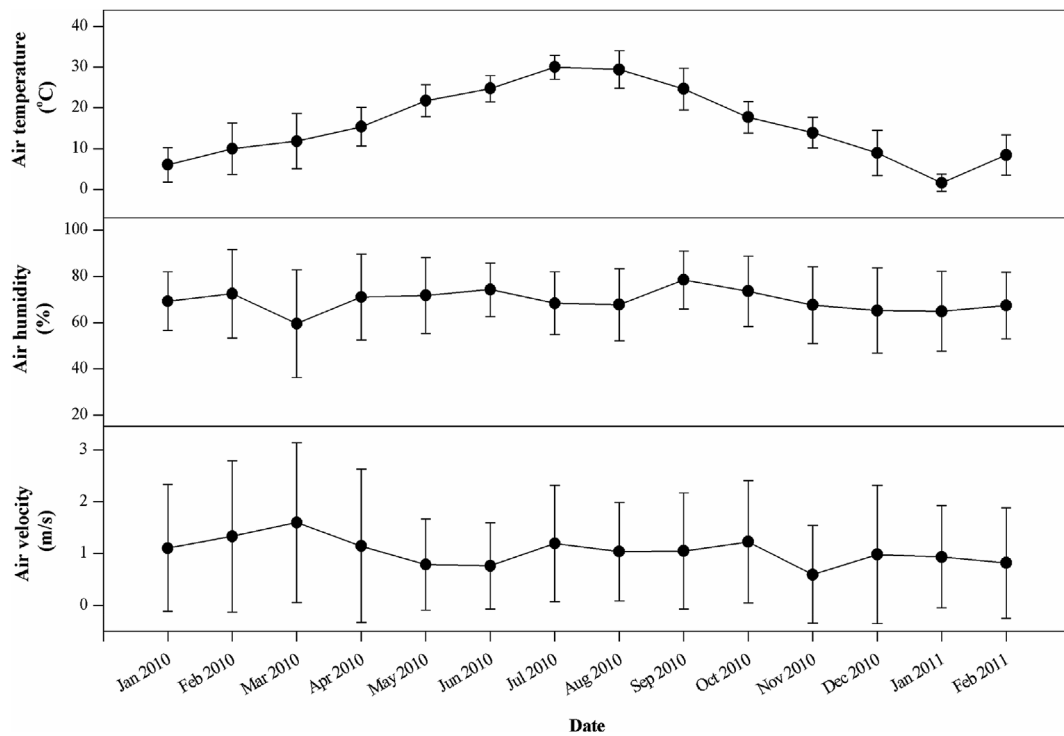


Fig. 2. Outdoor climate conditions (mean±SD) for different months during Jan. 2010–Feb. 2011.

Table 2

The statistical results of clothing insulation (clo) in different seasons.

Season	Min	Max	Mean
Spring	0.5	1.5	1.1
Summer	0.2	1.25	0.49
Autumn	0.4	1.83	1.06
winter	0.98	1.88	1.42

opposite trend against the outdoor temperature during the whole period of the survey. The slow variation in the daily mean clothing insulation was observed under high outdoor temperatures in summer and low outdoor temperatures in winter, respectively (within the red rectangle in Fig. 3).

3.3. The past outdoor temperatures and clothing insulation

Fig. 4(a) illustrates a gradual decay in the strength of statistical correlation between the daily mean clothing insulation on each day and the daily mean outdoor temperatures of the preceding 60 days before the day in which the mean clothing insulation was calculated. In particular, for 8 days before (Day -1 , -2 , ..., -8), the values of the correlation coefficient were higher than 0.85, which indicated strong effects of the daily outdoor temperatures of these previous days.

Fig. 4(b) shows the strength of statistical correlation between the daily mean clothing insulation on each day and the averaged outdoor temperatures for the preceding n days (< 60) before the day in which the mean clothing insulation was calculated. The value of the correlation coefficient reached the maximum at Days 1–8, which indicated the strongest cumulative effects of the outdoor temperatures of the preceding 8 days.

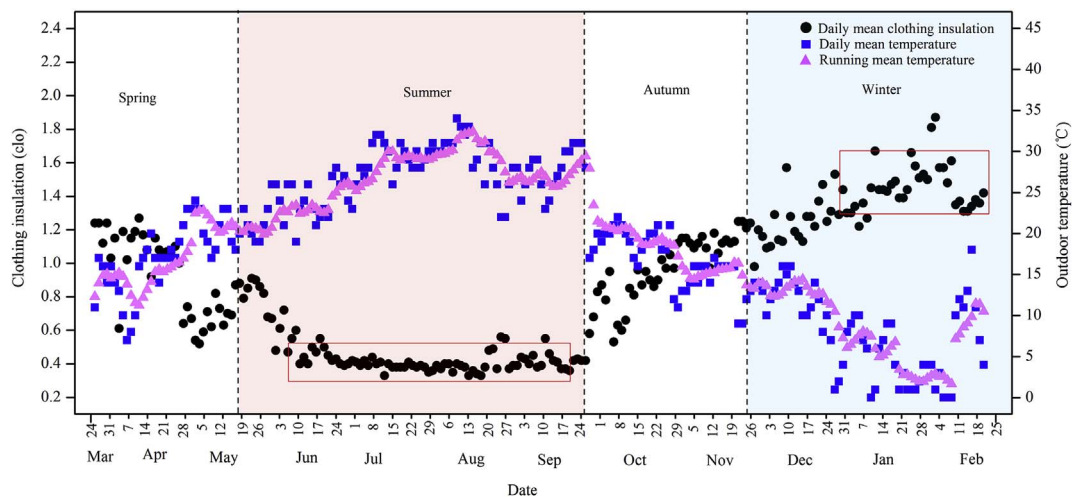


Fig. 3. The change of the daily mean outdoor temperature, the running mean outdoor temperature and the daily mean clothing insulation.

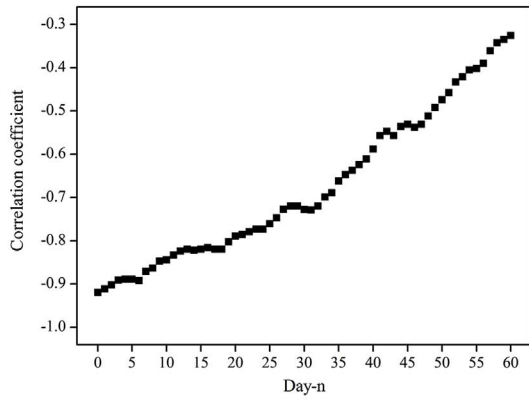
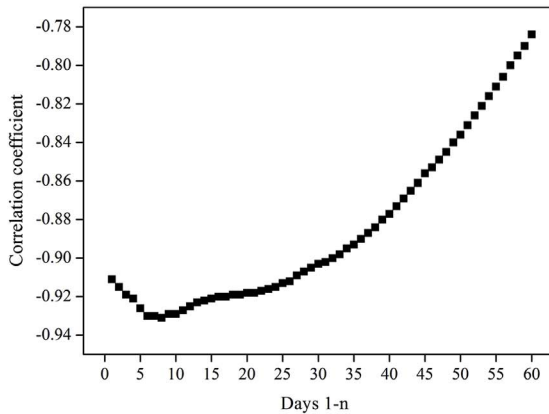
(a) The correlation with daily mean outdoor temperature on preceding n day(b) The correlation with averaged outdoor temperatures for preceding n days

Fig. 4. Statistical correlation between the daily mean clothing insulation and the past outdoor temperatures. Day- n means preceding n day. Days 1- n means the preceding days from 1th to n th.

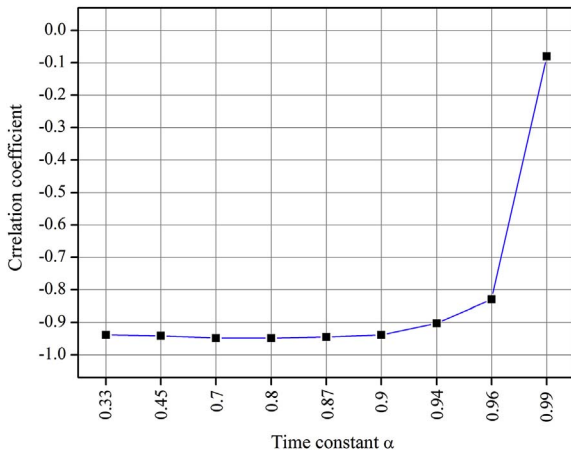


Fig. 5. Correlation coefficients for the relationship between the daily mean clothing insulation and the running mean outdoor temperature using different time constants.

3.4. The RM outdoor temperature

The RM outdoor temperature was calculated to reflect the effects of the past outdoor temperatures on the indoor clothing insulation, based on the daily mean outdoor air temperature using equation (4). Average outdoor temperature for 8 days before the starting day of the survey was used as the start value of the RM outdoor temperature, considering the cumulative effects shown in Fig. 4(b). The RM outdoor temperatures based on different values of the time constant α were correlated with the daily mean clothing insulation, respectively. Fig. 5 shows the

change of the values of the Pearson correlation coefficient with different values of α . The value of correlation coefficient rose to a maximum (-0.95) when α was 0.8, which indicated the highest correlation between the RM outdoor temperature and the daily mean clothing insulation. Therefore, the RM outdoor temperature calculated with the optimal value (0.8) of α was used in the indoor clothing model. Fig. 3 shows that the day to day variation in the RM outdoor temperature lagged behind the change of daily mean outdoor temperature; besides, the amplitude of variation reduced.

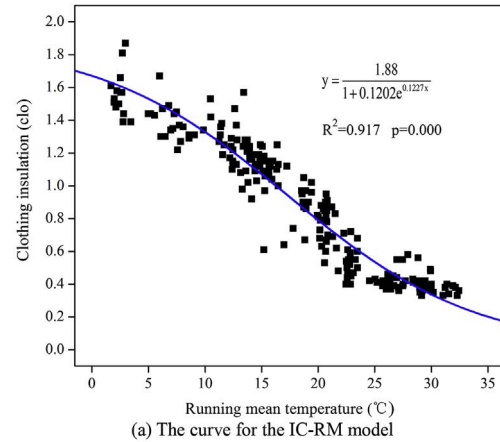
3.5. The indoor clothing model using RM outdoor temperature

The indoor clothing model using RM outdoor temperature (IC-RM model) was developed with the four parameters logistic function (equation (1)). Based on the field data, the proposed IC-RM model is given as,

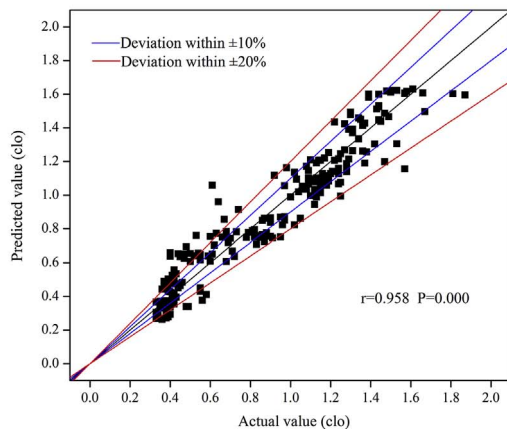
$$I_{cl} = \frac{1.88}{1 + 0.1202e^{(0.1227 \cdot Trm)}} \quad (R^2 = 0.917, P < 0.001) \quad (7)$$

where I_{cl} is daily mean clothing insulation (clo) and Trm means RM outdoor temperature ($^{\circ}\text{C}$).

In the IC-RM model, the upper limit for clothing adjustment was set at 1.88 clo, the maximum of individual clothing insulation in winter, assuming that the daily mean clothing insulation will increase close to the maximum with the decrease in outdoor temperature; and the lower limit was set at 0 clo instead of 0.2 clo the minimum clothing insulation. Here 0 clo is a supposed limit (not only for this case) for clothing adjustment at high temperatures assuming that people can gradually reduce their clothing insulation to a very low level close to 0 clo when



(a) The curve for the IC-RM model



(b) The relative deviation of the predicted mean clothing insulation

Fig. 6. The indoor clothing insulation model using four parameters logistic function (IC-RM model) based on the data from the survey.

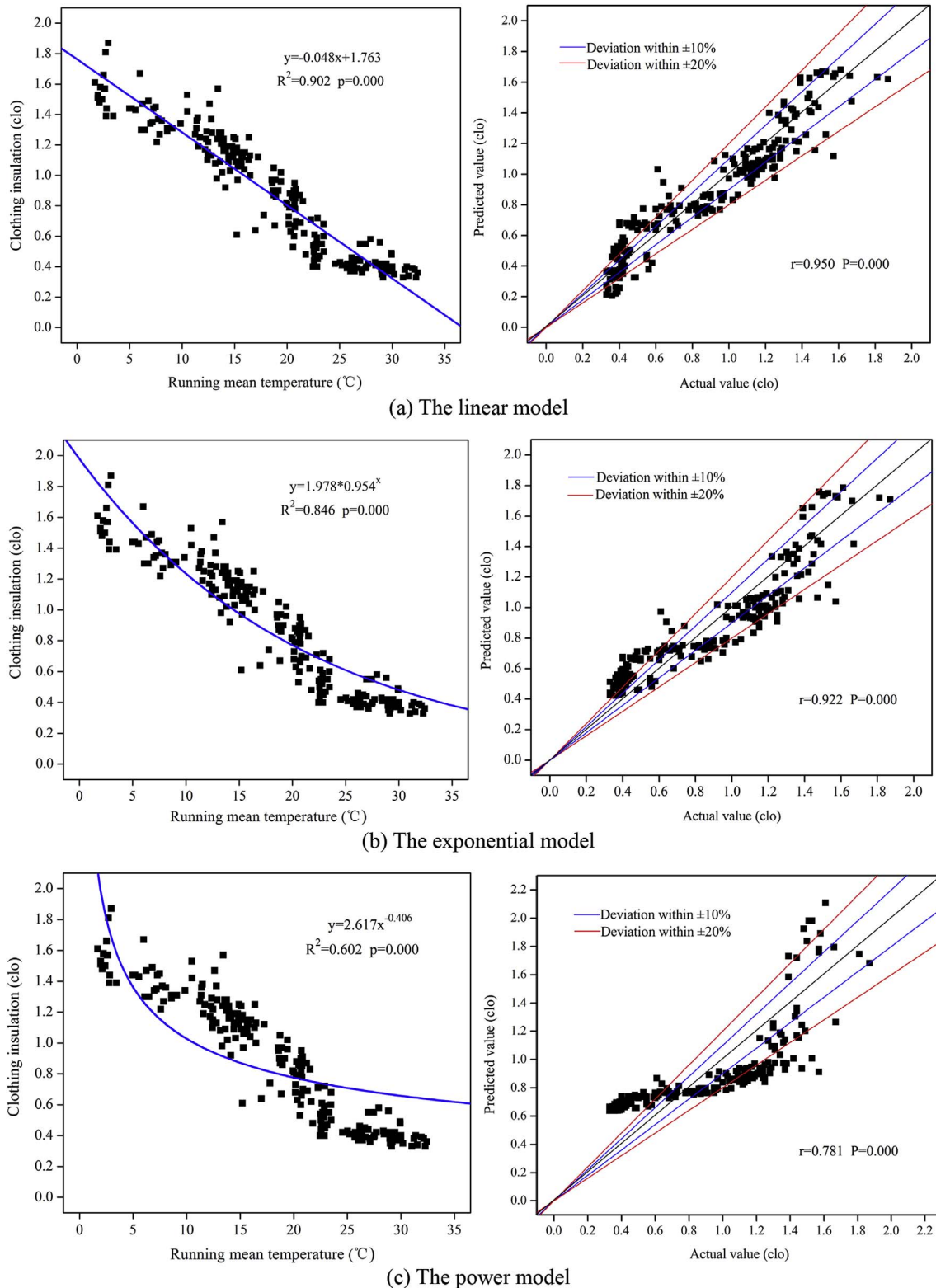


Fig. 7. The indoor clothing insulation model using linear, exponential and power functions based on the data from the survey.

the outdoor temperature increase to a very high level in summer. They might wear clothing made from special cool material or designed with special structure. The insulation for such clothing should be lower than the normal value listed in Table 1. Additionally, in this case the R^2 (0.917) for the IC-RM model using 0 clo as the lower limit was better than that (0.898) using 0.2 clo.

Fig. 6 gives the curve and accuracy of the IC-RM model. The curve

(Fig. 6(a)) well described the variation in the daily mean clothing insulation with the RM outdoor temperature with high value of the determination coefficient ($R^2 = 0.917$). The accuracy (Fig. 6(b)) of the IC-RM model shows that the deviation of 79% of the total samples was within 20%.

According to equation (3), the variation rate of clothing insulation reached the maximum value of 0.06 clo/°C at the RM outdoor

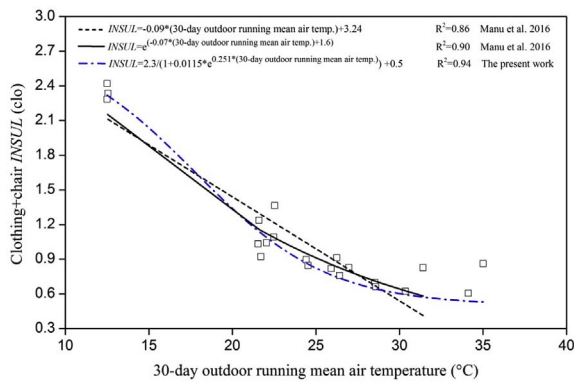


Fig. 8. The indoor clothing model fitted by the logistic function based on the field data in India. The data resource: Fig. 6 (NV) in Ref. [18].

temperature of 17.3 °C (the midpoint) and decreased to 0.04 clo/°C at 7.3 and 27.1 °C. Here, the temperature range between 7.3 and 27.1 °C is defined as the rapid clothing adjustment period (section 2 in Fig. 1(a)), considering that 0.04 clo is the minimum clothing insulation of underwear.

Fig. 7 illustrates the regression results and accuracy using three main existing models (linear, exponential and power function) based on the same field data. The performance of these functions were weaker than the logistic function, as reflected by the lower R^2 values and accuracy.

Additionally, the proposed logistic model was used to develop the relation between indoor clothing insulation and mean outdoor temperature based on the field data in the exiting reference [18]. Fig. 8 shows the regression results. As expected, the logistic model can explain more proportion in the change of the clothing insulation with the RM outdoor temperature than the existing models, as it possessed a higher R^2 value.

4. Discussion

This study presented clear evidence to support the assumption that the logistic function combined with RM outdoor temperature is appropriate to quantify the change of indoor clothing insulation considering the effect of thermal history. On the one hand, Fig. 3 shows the reversed change of the indoor clothing insulation against outdoor temperatures, with the low change rate under high outdoor temperatures in summer and low outdoor temperatures in winter. The diminished degree of freedom for clothing adjustment was also observed by some existing studies [e.g. 8,11,13, 14, 20]. This trend can be well described by the logistic function. In contrast to linear, exponential and

power functions (Fig. 7), the logistic function possessed higher value of R^2 (Fig. 6), which indicates that it can explain the change of the indoor clothing insulation more sufficiently; besides, the logistic function provided better prediction results, with the highest proportion of samples locating within the relation deviation of 10% and 20% (Table 3). Good performance can also be seen in Fig. 8 when the proposed logistic function was applied to the field data from the existing study [18]. It seems that the performance of the linear model was close to the logistic function. However, the linear model cannot reflect the decreased variation rate of the clothing insulation at high or low outdoor temperatures, which will lead to unreasonable results. For example, high temperature harms people and is becoming more and more common in China [27]. If the RM outdoor temperature rise to 37 °C, the daily mean clothing insulation reduces to a negative value (−0.0034) as shown in Fig. 7(a). A few studies tried to solve this problem by defining a minimum and maximum clothing level in their models [14,17,18]. However, the approach means that their regression models were available only when the clothing insulation was located in the limited range.

On the other hand, Fig. 4 shows the strong strength of statistical correlation between the daily mean clothing insulation and the outdoor temperatures for the preceding eight days before the day in which the mean clothing insulation was calculated. A similar variation was observed in the correlation between the daily mean clothing insulation and the outdoor temperatures for the preceding seven days [8]. Another study shows that the previous day's average temperature has a higher weight than the day's maximum temperature on clothing insulation [15]. These indicate the notable effects of the past outdoor temperatures (thermal history) on the indoor clothing insulation. The RM outdoor temperature well reflects the effect of the past outdoor temperatures and is a good predictor to indoor clothing insulation, as revealed by its very strong correlation ($r = 0.95$) with the clothing insulation (Fig. 5). Compared with the daily mean outdoor temperature for the current day (Day-0 in Fig. 4(a)), the RM outdoor temperature had a higher correlation coefficient for the relation with the clothing insulation. Additionally, the RM outdoor temperature exhibits much stronger relation with the clothing insulation than other indoor and outdoor climatic parameters, i.e. instantaneous indoor temperature, outdoor relative humidity and wind speed (see Appendix). Manu et al.'s result also shows a better performance to predict indoor clothing insulation using the RM outdoor temperature than the indoor operative temperature for naturally ventilated and air conditioning buildings [18].

The determination of the best value for the time constant α is the key to calculate the RM outdoor temperature. The value of α reflects the time period of adaption to weather change [16,28]. In this study, the best value of α was determined as 0.8, at which the strongest

Table 3

The proportion of samples within relation deviation of 10% and 20% for different clothing regression models.

Model	Deviation $\pm 10\%$		Deviation $\pm 20\%$	
	Number of samples	Proportion of samples	Number of samples	Proportion of samples
Linear	99	44	168	76
Exponential	26	12	80	36
Power	56	25	138	62
Logistic (IC-RM)	111	50	175	79

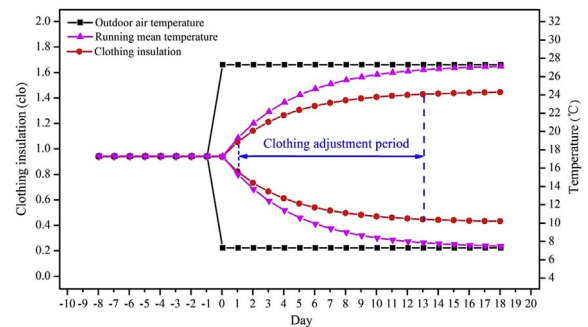


Fig. 9. The variation in clothing insulation after a step-change of the outdoor air temperature based on the proposed IC-RM model.

correlation between the daily mean clothing insulation and the RM outdoor temperature was obtained. Based on the best value for α , the time period of clothing adjustment is estimated as 13 days according to the method proposed by Liu et al. [28]. That means the indoor clothing adjustment will last 13 days until the clothing insulation keeps steady at a new value, after a sudden change of climate. In Changsha a sudden increase or decrease in outdoor temperature often occurs during the transition seasons from spring to summer or from autumn to winter, and the sudden change in outdoor temperature can reach 10 °C. Fig. 9 gives an example of the variation in the clothing insulation caused by a sudden change in the outdoor temperature, based on the IC-RM model. Assumed that the outdoor air temperature suddenly increased from 17.3 °C to 27.3 °C in one day, the clothing insulation will decrease gradually from 0.94 to 0.43 clo during 13 days and remained almost steady after the 13th day. The reversed trend can be observed for the clothing insulation after a sudden decrease of 10 °C in the outdoor temperature.

The clothing insulation adjustment predicted by the IC-RM model can be closely connected with adaptive thermal comfort. According to the IC-RM model, the indoor clothing insulation had the same time period of adaption (13 days) to the weather change as the neutral temperature, because the best value of the time constant α for the neutral temperature calculated with Fanger's PMV model was 0.8 based on the same survey [26]. The value of α for the RM outdoor temperature is also 0.8 in the adaptive comfort model proposed by EN 15251 [16]. That means the change of the neutral temperature kept step with the clothing insulation. The result supports the viewpoint that the clothing adjustment exerts important effect on the adaptive thermal comfort [4].

In brief, the proposed IC-RM model provides an improved method to quantify the change of indoor clothing insulation with weather. The values for the key parameters of the logistic function and the RM outdoor temperature in the IC-RM model were determined and validated based on the data from the survey conducted in two offices in Changsha China. However, these values might not be representative for office workers due to the limited field data. On the other hand, these values might not be applied to other climate zones or countries, considering that thermal adaption and cultural factors can affect the amount of clothing worn by different populations [18,29,30]. This is reflected by different rates of clothing insulation change with the RM outdoor temperature for cities in Germany (0.03 clo/°C) [17], in India (0.09 clo/°C) [18] and this city (max. 0.06 clo/°C). Therefore, the IC-RM model must be validated and adjusted according to different climate conditions and areas. The effect of age on clothing should also be considered. For example, the maximum winter clothing insulation (1.88 clo) for the

young students in this study is much lower than that (2.34 clo) for elderly female subjects in Ref. [31]. Additionally, the sensitivity of the indoor clothing adjustment to low temperature might be different from that to high temperature. For this asymmetric trend, the proposed model can be improved using asymmetric logistic model [32]. This needs to be investigated in future.

Further analysis will also be carried out to investigate outdoor clothing insulation adjustment based on the proposed IC-RM model, since outdoor thermal comfort is significantly influenced by the climate condition [33].

5. Conclusions

- (1) The indoor clothing insulation presented an opposite trend against the outdoor temperature. The variation rate in the clothing insulation reduced under high outdoor temperature in summer and low outdoor temperature in winter.
- (2) The past outdoor temperatures influenced the indoor clothing insulation. The outdoor temperatures of the preceding 8 days exerted the strongest cumulative effects.
- (3) The best value of the time constant was determined as 0.8 for the calculation of the RM outdoor temperature, which indicates the time period of indoor clothing adjustment to climate change is 13 days.
- (4) The proposed IC-RM model based on the logistic function exhibited better performance in quantifying the tendency for the variation in the indoor clothing insulation with the RM outdoor temperature.

The IC-RM model can be applied in adaptive thermal comfort evaluation considering the effect of climate change on clothing insulation. This model can also be applied in the energy consumption simulation in buildings considering the effect of clothing adjustment. These application can provide important basis to find reasonable balance between thermal comfort and energy consumption under the climate change.

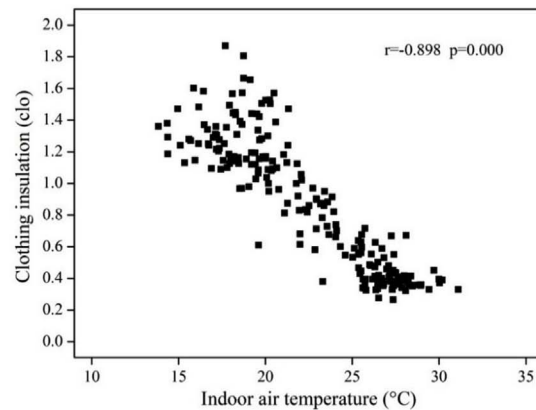
Competing financial interests

The authors declare they have no financial interests.

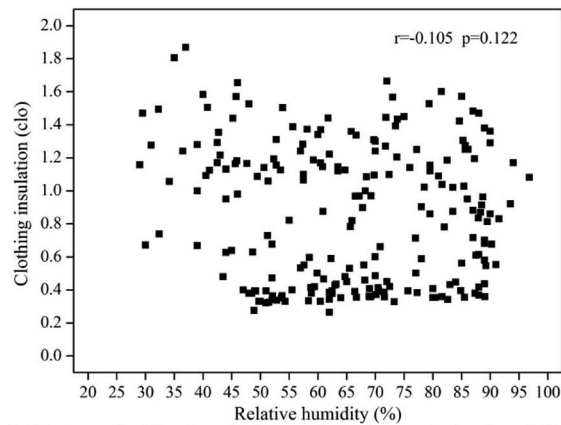
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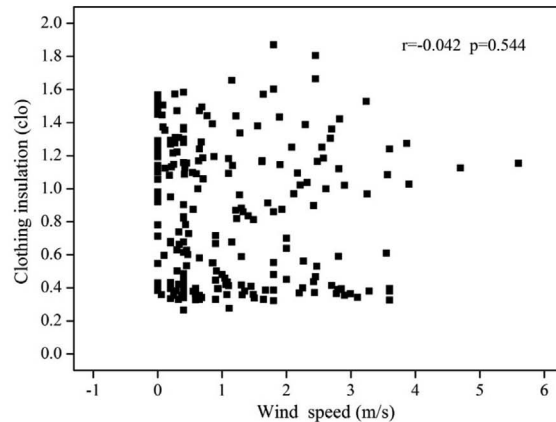
Appendix



(a) Indoor clothing insulation and indoor air temperature



(b) Indoor clothing insulation and outdoor relative humidity



(c) Indoor clothing insulation and outdoor wind speed

Fig. A1. The correlation between daily mean indoor clothing insulation and indoor air temperature, outdoor relative humidity and wind speed. r means Pearson correlation coefficient. p means significance level.

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